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LA-UR-79-3196

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SUBMITTED TO: 1979 Annual Meeting of the Optical Society of America
Rochester, NY
October 8-12, 1979

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Form No. 836 R3
St. No. 2629

UNITED STATES
DEPARTMENT OF ENERGY

INTERFEROMETRIC EVALUATION OF DIAMOND-TURNED MIRRORS FOR CO_2 LASER FUSION

James L. Munroe

The Laser Fusion Program at the Los Alamos Scientific Laboratory is developing high-energy carbon-dioxide lasers for the demonstration of scientific feasibility of laser fusion in the mid-1980's. This effort, supported by the Department of Energy, Office of Inertial Fusion, has the goal of providing fusion energy for commercial power to help satisfy the nation's future energy requirements.

The short-pulse, high-energy CO_2 laser is a very promising candidate for a fusion reactor system. It has a demonstrated efficiency in excess of 2 percent with a potential efficiency as high as 10 percent and, because it uses a gaseous laser medium, it can be designed to operate at the high repetition rates required for commercial power generation. The 10.6-μm wavelength has been demonstrated to be effective in producing thermonuclear yield at modest power levels.

There are presently two operational CO_2 laser-fusion systems at LASL; the 1-kJ Gemini system, and the 10-kJ Helios system. Under construction and scheduled for completion in mid-1984 is the 100-kJ Antares system. Significant thermonuclear yield is expected from Antares, but the major scientific and technical milestones of ignition and scientific breakeven appear to be beyond the capabilities of 100-kJ lasers.

Materials Consideration

The choice of materials for operation at a wavelength of 10.6 μm is limited. Laser fusion requires very short pulses, in the order of one nanosecond. Materials used must have sufficiently high damage thresholds, to routinely withstand the resulting high instantaneous power densities. Early in the laser train, before full amplification, one has a relatively wide choice of materials. After amplification, however, the energy densities and power densities become sufficiently high that the choice of materials becomes severely limited. The optics in the CO_2 lasers at LASL consist predominantly of polycrystalline sodium-chloride windows and copper-plated mirrors. The mirror substrates are aluminum or aluminum-bronze, a copper alloy.

The choice of these materials stems from many considerations, including cost, stability, strength, and damage resistance. The choice of plating copper onto a substrate combines the virtues of very pure copper with the dimensional stability characteristics of an alloy. For our smaller mirrors, which are typically conventionally manufactured, the substrate choice is aluminum bronze. Aluminum bronze, being approximately 90 percent copper, has a thermal expansion coefficient very close to that of the plated, pure copper. For our larger mirrors, which are typically single-point diamond turned (SPDT), the substrate choice is aluminum alloy type 2124. For the larger mirrors, the sheer weight of a much heavier bronze substrate would introduce more serious complications than the small, residual bimetal effect between the aluminum substrate and the plated copper. The Antares environment will be controlled to $\pm 1^{\circ}C$, which effectively eliminates the bimetal effect.

Antares will contain in excess of 500 large copper-plated mirrors. They will be large in the sense of having characteristic dimensions in excess of 12 inches. None of these mirrors will be round but will have shapes which are approximately trapezoidal. Also, there is little allowance for edge roll; these mirrors must maintain optical quality nearly out to the edge. These considerations are some of the reasons that the large Antares mirrors are being fabricated by the relatively new technology of single-point diamond turning. Single-point diamond turning has made enormous strides in the past few years and is now capable of routinely producing components of more than sufficient quality to result in diffraction-limited system performance at the Antares wavelength of 10.6 μm. Surface figure is now typically between one to one-and-one-half visible fringes peak-to-valley with surface finishes better than two micro-inches peak-to-valley.

In single-point diamond turning, the part is literally cut on a lathe. The mirror substrate is rotated about the axis of the lathe while a diamond tool moves radially across its face. Any geometry which can be cut on a lathe can be manufactured by single-point diamond turning.

Obviously, the characteristics of the parts manufactured by single-point diamond turning will be very different than the comparable parts manufactured by an optician. The type of information that one seeks during evaluation of the parts must be based on the method of manufacture. Data that can be used to improve the process are the following:

Average Radial Profile

The manufacturing process is radially symmetric. The only control the machinist has over the surface figure is the motion of the diamond tool across the face of the rotating mirror blank. He has the ability to introduce or remove optical power and spherical aberration of any required order, terms which vary radially but not azimuthally. Thus, the best piece of data that one can give to the machinist is the average radial profile whereby any azimuthal variations have been averaged out.

Done correctly, average radial profile gives the machinist a direct reading of the errors in the cutting process and can be used to directly generate a correction tape. For this reason, the average radial profile should be centered at the lathe axis so that it accurately represents the cutting geometry.

Optical Power in Flats

Because the Antares mirrors are of copper plated onto an aluminum substrate, there is a small sensitivity to temperature whereby the mirror will tend to bow spherically with temperature changes. The only way to control this is to control the ambient temperature at both manufacture and final application. The presence of optical power in a flat is frequently an indication of a temperature-related problem and, if present, should be flagged separately from the average radial profile.

Astigmatism

Astigmatism in a diamond-turned part is usually an indication of a mounting problem in putting the mirror substrate onto the lathe.

Typically, the substrate is somewhat twisted by the mount and the radially symmetric mirror geometry is cut onto the twisted substrate. When the mirror is released from the holding fixture, it untwists and introduces astigmatism into the mirror contour. Diamond-turned mirrors must be watched carefully for the presence of astigmatism indicating mounting problems.

Surface Finish

Surface finish is the fine groove-like structure that tends to give diamond-turned mirrors the appearance of a very fine phonograph record. Surface finish problems tend to arise from vibrations being transmitted through the diamond tool and are frequently the result of beat patterns from two dissimilar frequencies in the environment. The surface finishes of the Antares diamond-turned mirrors are becoming sufficiently good that they pose little problem for performance at the Antares wavelength of 10.6 μm, but remain a concern for the alignment system which uses visible light. Surface finish has been improving rapidly as the vibrational sources are identified and eliminated.

Considerations for System Performance

After the part is fabricated and accepted for installation into the system, it is no longer a question of "How do I make the part better" but rather what effect this part will have on system performance. To understand how the component affects system performance, it is necessary to briefly review the performance requirements of Antares and how these requirements are related to component quality.

The performance requirements for Antares are in terms of encircled energy. The complicated form of the Antares aperture, an annulus containing 12 quasi-trapezoidal subapertures, makes any attempt at a rigorous solution a very formidable task. Fortunately, it can be shown that several simplifying assumptions and approximations can be used to achieve an engineering solution which allows the encircled energy to be closely estimated.

We find that window thickness variations result in the incoherent summation of the diffraction patterns from the individual subapertures. For purposes of calculating encircled energy, the diffraction pattern need only be calculated for one window and the result multiplied by 12.

There are additional simplifications. We examine the properties of a circular aperture having the same area as the quasi-trapezoidal segment. The circle reduces the diffraction integral to a one-dimensional integral and has the additional advantage that the encircled energy distribution calculation is also a one-dimensional integral.

When we calculate the encircled energies from these two apertures, we find that the true segment and the equi-area circle result in distributions within a few percent of each other. Wavefront error from manufacturing will bring these curves even closer together. Encircled energy is thus very insensitive to azimuthal variations.

Given that we can accurately model the Antares geometry by an equivalent circular aperture, we can proceed to approximate the effects of component manufacturing error. We first observe that each beam will encounter a large number of optical components, some 20 surfaces in the power amplifier and target chamber alone. With this many optical surfaces contributing, the net wavefront error should not be expected to show any pronounced directional preference. There is no basis for assuming a wavefront error other than circularly symmetric. A circularly symmetric wavefront error model complements the equivalent circular aperture model.

Now we need to consider the radial variations in wavefront error. This is best done by thinking of the radial variations in terms of a Fourier decomposition, radial sinusoids from the center of the aperture to the edge. Next we divide the spatial frequency components into high-frequency terms and low-frequency terms.

Looking first at the high spatial frequency terms, we examine each spatial frequency separately. Each frequency defines a radial phase grating with the image corresponding to the zero order. The remaining orders form an annular rings of very low energy density which is effectively lost.

What we observe when high frequency terms are present is that the image loses energy in a fashion which leaves the relative distribution unchanged. The loss of energy is indistinguishable from a reflection loss. In fact, that there is a loss might only be established by very accurate calorimetry. We also observe that the energy lost is a function of the amplitude and is independent of frequency. The frequency determines where the energy goes, but we are only concerned that it is gone.

This loss can be treated as an equivalent reflectance and plotted as a function of the amplitude. For a more complicated high spatial frequency error form, superposition would be used to combine the effective reflectances for all the spatial frequency components.

The low spatial frequency errors represent what is normally referred to as figure error. In the presence of figure error we observe a change in the relative energy distribution of the image. The peak intensity drops and energy is transferred from the center toward the wings of the pattern. The presence of figure error does not result in a measurable loss of energy, only a redistribution.

Using the same arguments that lead to the rotationally symmetric assumption, we can also claim that the probability of the error occurring anywhere within the aperture is relatively uniform. That is, there is no reason to assume that the dominant form of figure error will come from buildup of such localized phenomena as turned edges.

In looking for an analytical model which combines rotational symmetry with an error form relatively evenly distributed across the aperture, we find that balanced primary spherical aberration satisfies the requirements very well. In fact, it is probably somewhat pessimistic in that small amounts of balanced spherical rapidly transfers energy far into the wings of the image. Balanced primary spherical aberration is the combination of third-order spherical aberration with focus error of equal magnitude but opposite sign.

This model does not assume that each surface contributes figure error in the form of balanced spherical aberration, but that for purposes of computing encircled energy, the final wavefront error can be satisfactorily modeled this way.

The result of this model is the relationship between encircled energy and RMS wavefront error in the final wavefront. This can, in turn, be related to the individual component qualities by setting the final RMS wavefront error equal to the root-sum-square of the individual component contributions.

To apply the results of this model to parts actually measured, we find that we are primarily concerned that there are not systematic errors occurring on sequential parts in each optical train. The presence of systematic errors would require the algebraic summing of the individual errors rather than the root-sum-squaring which is the basis of our model. The best example of a systematic error would be astigmatism introduced by mounting stresses when the part was cut on the machine. Given that the parts are cut correctly and that the errors are due to random factors, that is the errors are different in form on each part, the following pieces of data can be related to final system performance.

The RMS Wavefront Error Contribution

Within the accuracy of the model, this should be sufficient to calculate the resulting encircled energy distribution. The individual RMS wavefront error contributions along each optical train can be root-sum-squared to obtain the final RMS wavefront er ... the exiting wavefront. Through our model, it can directly give the resulting encircled energy distribution. It can also be used to calculate the resulting Strehl ratio in the image but this value is of lesser importance for laser fusion. In principle the RMS wavefront error contains ..most all of th~ required information.

Aberration Coefficients, Low Spatial Frequency

The low spatial frequency aberration coefficients correspond to figure error and are useful as a check on the validity of the model. The RMS wavefront error was a measure of how much energy is transferred into the wings whereas the low spatial frequency aberration coefficients describe where they went. Although laser fusion is principally concerned with encircled energy, information on the azimuthal distribution provides insight into what kinds of errors are present. The low spatial frequency aberration coefficients provide information on the azimuthal distribution.

Aberration Coefficients, Medium Spatial Frequency

The medium spatial frequency aberration coefficients redistribute energy far into the wings; so far, in fact, that they are effectively no longer part of the image. The medium spatial frequency aberration coefficients redistribute the energy over such large areas that the resulting energy densities are infinitesimally small and the energy is effectively lost. The medium spatial frequency aberration coefficients can be equated to an equivalent reflectance loss with the important difference that this reflection loss does not correspond to an absorption increase and does not affect the damage threshold.

Surface Finish

The surface finish is the very high spatial frequency detail comparable to the grooves in a record. The effects of surface finish on 10-micron performance is not calculable with scalar diffraction theory since the period is less than the wavelength of the 10-micron light. The surface finish amplitude, in terms of the 10-micron wavelength, has a negligible effect on 10-micron performance. Surface finish is of more importance for a visible alignment scheme where it again corresponds to an effective reflectance loss.

Conclusion

In conclusion, we have seen that single-point diamond-turned optics exhibit different characteristics than conventionally manufactured optics and the type of information required by the machinist is quite different than the information that would be required by an optician. We have also seen, with Antares being a good example, that single-point diamond turning allows the manufacture of geometries and scales that might be unthinkable if conventional manufacturing were to be used. As single-point diamond turning continues to improve in quality, machined optics will find application at shorter and shorter wavelengths. A whole new formalism to describe manufacturing errors in terms meaningful to the machinist will have to be developed. Similarly, as designers learn to take advantage of the design freedoms available from single-point diamond turning, systems will begin to incorporate more non-circular elements. It will rapidly be appreciated that the standard seidel formalism which assumes circular symmetry is of little, if any, use and new ways must be devised to relate system performance to component quality. We hope that the work done on Antares will help serve as a beginning.